OBSERVATION AND INTERPRETATION OF
METEOROID IMPACT FLASHES ON THE MOON

LUIS R. BELLOT RUBIO
Instituto de Astrofísica de Canarias, La Laguna, Tenerife, Spain
E-mail: lbellot@ll.iac.es

JOSE L. ORTIZ
Instituto de Astrofísica de Andalucía, CSIC, Granada, Spain
E-mail: ortiz@iaa.es

PEDRO V. SADA
Universidad de Monterrey, Monterrey, México

Abstract. The first unambiguous detection of meteoroids impacting the night side of the Moon was obtained during the 1999 Leonid storm. Up to eight optical flashes were recorded with CCD video cameras attached to small telescopes on November 18, 1999. Six impacts were videotaped by at least two independent observers at the same times and lunar locations, which is perhaps the strongest evidence for their collisional nature. The flashes were clearly above the noise and lasted for less than 0.02 s. Although previous observational efforts did not succeed in detecting impact flashes, additional candidates have been reported in the literature. The evidence accumulated so far implies that small telescopes equipped with high speed cameras can be used as a new tool for studying meteoroid streams, sporadic meteoroids, and hypervelocity collisions. In this review we discuss the various intervening parameters for detectability of flashes on the night side of the Moon (geometrical effects, contamination by scattered light from the day side, and properties of the meteoroids such as speed and flux of particles). Particular emphasis is placed on the analysis of the observations in order to derive relevant physical parameters such as luminous efficiencies, impactor masses, and crater sizes. Some of these parameters are of interest for constraining theoretical impact models. From a simple analysis, it is possible to derive the mass distribution of the impactors in the kg range. A more elaborate analysis of the data permits an estimate of the fraction of kinetic energy converted to radiation (luminous efficiency) if the meteoroid flux on the Moon is known. Applied to the 1999 lunar Leonids, these methods yield a mass index of 1.6 ± 0.1 and luminous efficiencies of 2×10^{-3} with an uncertainty of about one order of magnitude. Predictions of visibility of the major annual meteor showers are given for the next few years. These include the forthcoming 2001 Leonid return, for which we estimate detection rates in the visible.

Keywords: Hypervelocity impacts, Leonids 1999, luminous efficiencies, lunar craters, meteoroids, meteors, Moon

1. Introduction

The search for meteoroid impacts on atmosphereless bodies has attracted some interest because of its potential for deriving information

on the physical properties of the impactors (chemical composition, density, structure, etc), their mass distribution and fluxes, and, even, the properties of the target surface material. Planets and satellites may be regarded as huge detectors whose collecting areas permit the observation of very large meteoroids in much less time than that required by ground-based monitoring of the Earth's atmosphere. In this regard, the Moon is the first natural body to scrutinize, not only because it is the object closest to Earth, but also because the meteoroid population in the neighborhood of the Moon is reasonably well known from the observation of terrestrial meteors. This implies that results from lunar impacts can be directly compared with results from more conventional techniques.

Meteoroids impacting the Moon give rise to a variety of essentially different phenomena that allow their detection. These include seismic waves, enhancements of the tenuous lunar atmosphere, and light flashes. Analysis of data from the Apollo lunar seismic network (Oberst and Nakamura, 1991) established that the 1974 Leonid shower produced signals consistent with impacts of meteoroids in the mass range from 0.1 to 1 kg. Other meteor showers could also have been detected by this network. Transient enhancements in the constituents of the tenuous lunar atmosphere may reveal the occurrence of meteoroid impacts. The Moon cannot retain any gaseous species for a long time, so continuous resupply is necessary. Impact-driven vaporization has been proposed as the most likely source of sodium and potassium in the lunar atmosphere, and indeed significant increases in lunar sodium were detected at the time of the 1997 and 1998 Leonids (Hunten *et al.*, 1998; Verani *et al.*, 1998; Wilson *et al.*, 1999). However, monitoring of the Moon during other meteor showers such as the Quadrantids did not reveal any variation of sodium in the atmosphere (Verani *et al.*, 1999).

It has been known for some time that impacts of meter-sized bodies on the Moon should cause optical flashes detectable with photometer technology (Melosh *et al.*, 1993), but the population of objects that are big enough is low and no unambiguous impact flashes have been recorded. Inspired by the successful detection of comet Shoemaker–Levy 9 collision with Jupiter in 1994, a systematic search for fainter events on the Moon was started in 1997 using more sensitive techniques based on CCD technology (Ortiz *et al.*, 1999). Although no impacts were unambiguously detected, it was stressed that a small 0.25 m telescope could easily observe flashes from meteoroids releasing energies well below 5×10^6 J in the visible range. It was also pointed out that the 1999 Leonid storm would provide a unique opportunity to record the optical flashes associated with meteoroids impacting the Moon due to the greatly enhanced flux of particles expected and the favorable

geometrical conditions of the encounter. Other attempts to detect lunar impact flashes include the ALPO's Lunar Meteor Search program from 1955 to 1965 (see Westfall 1997) and the optical transient survey of the Moon conducted by Beech and Nikolova (1999). Unfortunately, none of these efforts led to unequivocal observations of light flashes on the Moon.

The first unambiguous detection of lunar impact flashes was indeed obtained during the 1999 Leonid shower. These observations open the door to the remote sensing of objects and physical processes that would be difficult to observe otherwise. In particular, lunar impact flashes may provide important information on the physics of hypervelocity impacts. Experimental work has been carried out for low velocity collisions (e.g., Schultz, 1996, Kadono and Fujiwara, 1996), but high velocity impacts such as those involving meteoroids are much more difficult to reproduce in the laboratory. For this reason, knowledge of the characteristics of such events is primarily based on numerical simulations. Most of these studies consider impactors of asteroidal composition and, therefore, their results are not directly applicable to collisions involving cometary material. The analysis of real lunar impacts makes it possible to estimate key parameters that help constrain numerical simulations.

In this review we address the observational aspects of meteoroid impact flashes on the Moon. Section 2 deals with the detection of lunar flashes during the 1999 Leonids. The interpretation of the observations is the subject of Section 3. We describe how to estimate luminous efficiencies, mass distribution indices, impactor masses, and crater sizes. In Section 4, some results from numerical simulations of hypervelocity impacts are presented. Section 5 deals with the various conditions for the visibility of meteor showers on the Moon. Finally, Section 6 is devoted to calculating impact detection rates for the major annual meteor showers, with emphasis on the forthcoming Leonid showers. Hints for successful observations are given throughout the paper.

2. Observation of the 1999 lunar Leonids

Numerical simulations of the Leonid stream evolution (McNaught and Asher, 1999, Brown, 1999) suggested the possibility of storm level activity from the shower on November 18, 1999 at the time when the Earth was to cross the dust trail generated by 55P/Tempel–Tuttle in 1899. Ortiz *et al.* (1999) had previously pointed out that geometric conditions would be favorable during the night of maximum activity. These expectations prompted several groups to monitor the night side of the Moon in search for Leonid impacts. Soon after the 1999 Leonid

Table I.

Impact number	Time (UTC)	Magnitude	Lunar position		Observers
			Latitude	Longitude	
1	03:05:44.89	+5	40 ± 1 N	65 ± 1 W	DP, DD
2	03:49:40.38	+3	3 ± 1 N	48 ± 1 W	DP, DD, PS, RF
3	04:08:04.10	+5	15 ± 1 S	78 ± 1 W	DP, DD
4	04:32:50.79	+4	21 ± 3 N	51 ± 3 W	PS
5	04:34:49.52	+7	21 ± 3 N	38 ± 3 W	PS
6	04:46:15.52	+3	14 ± 1 N	71 ± 1 W	BC, DD
7	05:14:12.92	+6	15 ± 1 N	58 ± 1 W	PS, DD
8	05:15:20.92	+5	21 ± 1 N	59 ± 1 W	PS, DD

storm materialized on Earth, reports on the detection of lunar flashes were issued (Dunham, 1999). Although several 1 m telescopes were scheduled for observing the Moon at Calar Alto Observatory, Sierra Nevada Observatory, and Teide Observatory (all three in Spain), bad weather or technical problems prevented their use. Fortunately, positive observations came from smaller telescopes operated by B. Cudnik (0.36 m aperture, Columbus, TX, USA), D. Dunham (0.13 m, Mount Airy, MD, USA), R. Frankenberger (0.2 m, San Antonio, TX, USA), D. Palmer (0.13 m, Greenbelt, MD, USA), and P.V. Sada (0.2 m, Monterrey, México). At least eight impact flashes were videotaped by the last four observers, all using CCD cameras attached to their telescopes. For a complete description of the observations, we refer the reader to Dunham *et al.* (2000) and Ortiz *et al.* (2000). Observers used different, sometimes overlapping, fields of view. This turned out to be useful for confirming impact flashes, but implies that the individual observations cannot be combined into a single analysis due to the different lunar areas monitored.

Table I summarizes the observational data for the eight light flashes found by visual inspection of the tapes. The last column gives the initials of the observers who recorded the flashes. Their maximum magnitudes (in the wavelength range 0.4 to 0.9 μm) were obtained from comparison with the signals of reference stars and should be accurate to within $\pm 1^m$. The selenographic locations of the flashes in Dunham's records were determined by fitting the limb, and are uncertain by $\pm 1°$. The locations of the impacts detected by Sada were calculated by means of interpolation in time between two recognizable lunar features that drifted within the field of view due to inaccurate tracking of the telescope. The events summarized in Table I were very brief. They are

Figure 1. Half-frame images of the five light flashes recorded by P.V. Sada on November 18, 1999 (flashes 2,4,5,7, and 8 in Table I, respectively). These are 53×53 arcsec enlargements of the original 8×6 arcmin field of view.

mainly seen in half-frames (0.0167 s), the brightest flashes showing a much fainter (typically 3–4 mag) afterglow in the following half-frame.

All the impact flashes, except 4 and 5, were videotaped by at least two independent observers. Both times and selenographic positions are coincident, making a strong case that the flashes are indeed the result of Leonids colliding with the Moon. Alternative explanations not related to meteoroid impacts include cosmic rays and specular reflection of sunlight from artificial satellites or space debris. Cosmic rays can be ruled out because they usually affect a few pixels of the detector, whereas the observed flashes span a larger detector area. Another proof that cosmic rays were not responsible for the flashes comes from the fact that Sada's telescope was somewhat defocused at the time of the two last impacts, with the result that the central obstruction of the secondary mirror is clearly seen in the images (Fig. 1). This feature is very difficult to explain in terms of cosmic rays hitting the detector. On the other hand, the flashes occurred close to local midnight with the Moon at high altitude above the local horizon, which strongly suggest that the events are not due to objects in low orbit around the Earth. Moreover, Dunham *et al.* (2000) note that none of the known geosynchronous satellites were near the Moon at the time of the observations. These considerations, together with the fact that the lunar Leonids peaked at about 04:02 UT according to numerical calculations (Asher, 1999), provide compelling evidence for the impact origin of the flashes.

3. Analysis of the observations

High speed collisions such as those of meteoroids striking the Moon are difficult to reproduce in the laboratory because we still do not have means of accelerating the required masses to velocities typical of meteoroids. As a result, the physics of hypervelocity impacts is studied

through both numerical simulations and scaling of low-velocity experiments. The analysis of lunar flashes makes it possible to improve this situation by providing empirical values of key parameters describing these events. In addition, light flashes allow us to monitor the meteoroid population in a mass range hitherto unreachable from Earth by conventional techniques. All these advances hinge on a relatively accurate knowledge of the properties of the impactors, most notably their velocities and fluxes on Earth. This section is devoted to providing examples of the capabilities of the analysis of lunar flashes by focusing on the inference of luminous efficiencies, the mass distribution index of the particles, impactor masses, and crater sizes.

3.1. DETERMINATION OF LUMINOUS EFFICIENCIES

For several reasons, a key parameter in hypervelocity impacts is the luminous efficiency η —the fraction of the initial kinetic energy converted into radiation. Knowledge of this parameter allows us, for example, to estimate impactor masses. It also permits the inference of meteoroid bulk densities by constraining theoretical impact models. Prior to 1999, the emphasis of numerical simulations was on particles of asteroidal composition moving at several km s^{-1}. Depending on the properties of the projectile and target material (chemical composition, impact velocity, etc), the resulting luminous efficiencies varied from 10^{-5} to 10^{-3} (Nemtchinov *et al.*, 1998b). Very few simulations had been carried out for particles of cometary composition, and these were invariably restricted to small velocities. Under such conditions, no reliable estimate of η in impacts involving Leonid meteoroids was available prior to the 1999 return of the shower. In addition, theoretical models had suggested that, for fixed velocities and meteoroid bulk densities, luminous efficiencies might depend on impactor mass, incidence angle, and even the lunar relief (Nemtchinov *et al.*, 1998a).

Clearly, theoretical models may benefit from luminous efficiencies derived empirically. Under certain conditions, it is possible to infer reliable values of η from the analysis of optical flashes on the Moon. This was done for the first time by Ortiz *et al.* (2000) and Bellot Rubio, Ortiz, and Sada (2000). The basic idea is that the observed cumulative number of impacts within the field of view will match the expected number only when the true luminous efficiency is used to calculate the latter. For this method to work, it is necessary to know the meteoroid flux on the Moon at the time of the observations.

The cumulative flux distribution of meteoroids of mass m is given by

$$F(m) = F(m_0) \left[\frac{m}{m_0}\right]^{1-s},$$ (1)

where $F(m)$ represents the flux of particles whose mass is higher than m, m_0 is the mass of a shower meteoroid producing a (terrestrial) meteor of magnitude +6.5, and s is the so-called mass index. For most meteor showers, both $F(m_0)$ and s are well known from visual observations on Earth.

Substituting m in Eq. 1 by $2E/V^2$, with V the meteoroid velocity, the cumulative flux of particles as a function of their kinetic energy E can be written as

$$F(E) = F(m_0) \left[\frac{m_0 V^2}{2}\right]^{s-1} E^{1-s}.$$ (2)

On the other hand, the energy per unit area reaching the Earth can be approximated by

$$E_d = \frac{E}{f\pi R^2}\, \eta,$$ (3)

where η is the luminous efficiency, and R is the Moon–Earth distance. The coefficient f describes the degree of anisotropy of light emission. It should be 2 if light is emitted isotropically from the surface, or 4 if light is emitted from very high altitude above the Moon's surface.

The number of events above an energy per unit area E_d reaching the telescope in a time interval Δt can therefore be expressed as

$$N(E_d) = \int_{t_0}^{t_0+\Delta t} F(m_0, t) \left[\frac{2f\pi R^2}{\eta m_0 V^2}\right]^{1-s} E_d^{1-s}\, A\, dt,$$ (4)

where A is the lunar area perpendicular to the radiant direction within the field of view. $N(E_d)$, which depends on η, is the quantity to be compared with the observations.

Figure 2 presents the results of this method applied to the 1999 lunar Leonids (Bellot Rubio, Ortiz, and Sada, 2000). The flux profile entering the calculations is taken to be gaussian in shape with a peak of 10 km^{-2} hour^{-1} and a FWHM of 45 min. The mass of a Leonid meteoroid producing a meteor of magnitude +6.5 is $m_0 = 2 \times 10^{-8}$ kg according to Hughes (1987). For the mass index we use $s = 1.83$ in the magnitude range -1 to $+6$ and $s = 1.87$ for brighter meteoroids. Inspection of Fig. 2 reveals that the observational data at the high-energy end are best matched by a luminous efficiency $\eta = 2 \times 10^{-3}$. We estimate this value to be uncertain by an order of magnitude or
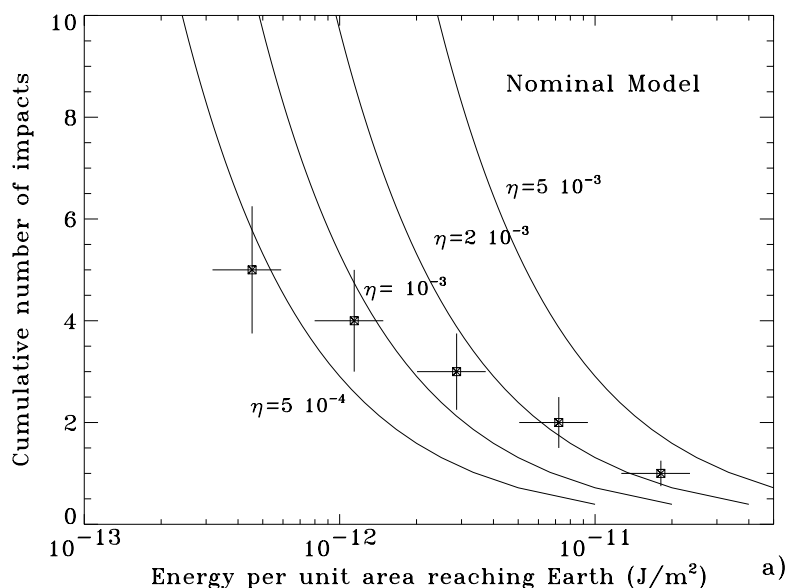
Figure 2. Comparison between observed (open squares) and expected (solid lines) cumulative number of 1999 Leonid impacts as a function of the energy received on Earth for several luminous efficiencies. From Bellot Rubio *et al.* (2000). Note that some of the faintest flashes may have been missed (see text for details).

less (see the discussion in Bellot Rubio *et al.*, 2000). In interpreting Fig. 2 it is necessary to bear in mind that some faint flashes may have been missed as they occurred near the sensitivity limit of the camera. This probably accounts for the deviation of experimental points with respect to the $\eta = 2 \times 10^{-3}$ curve at the lower-energy end. However, such deviation might also reflect a possible variation of η with mass, the smaller impactors converting less kinetic energy into light and vice versa. Unfortunately, the small number of flashes available for analysis implies that the issue of a possible mass dependence of η cannot be settled at the moment.

The 1999 lunar Leonids demonstrate the feasibility of estimating luminous efficiencies from real impacts. The value obtained so far, $\eta \sim 2 \times 10^{-3}$, applies only to Leonid meteoroids because η may be highly dependent on velocity. It would be desirable to carry out the same analysis for other meteor showers and impact geometries in order to investigate the dependence of η on parameters such as velocity and incidence angle. Other investigations appear to require similar or slightly larger luminous efficiencies for explaining an additional impact flash that might have occurred on the Moon in July 1999 (Ortiz *et*

al., 2000), but lack of knowledge of the meteoroid velocity complicates the interpretation to a large extent. The advantage of monitoring the major annual meteor showers on the Moon is that the meteoroid velocity is known from Earth-based photographic observations. For reliable inferences of the luminous efficiency, a statistically significant number of events need to be accumulated. Systematic campaigns involving telescopes of various sizes can certainly provide the necessary observations.

3.2. DETERMINATION OF THE METEOROID MASS DISTRIBUTION

The Moon, as a huge collecting area, permits the detection of very large particles in reasonable time intervals. This makes the characterization of such particles possible, thereby extending our knowledge of the properties of meteoroid streams to the high-mass end. From sufficient observational data it would be possible, for instance, to determine the mass of the largest particles present in the dust trails that give rise to meteor showers on Earth. Whipple's (1951) comet model provides an estimate of this limit as a function of certain comet and meteoroid parameters (see also Jones, 1995), but testing this formulation empirically has proved difficult. Not only can the upper mass limit be obtained from the analysis of lunar impacts, but also the mass index s describing the meteoroid population according to Eq. 1. Very remarkably, the inference of s is independent of η provided the luminous efficiency does not vary with m. This makes it possible to estimate the mass index directly from the observations *without any explicit knowledge of* η. Such a mass index may be necessary to evaluate Eq. 1 if the indices derived from visual observations do not apply to the larger lunar impactors.

Equation 1, with the help of Eq. 3, can be rewritten as

$$F(m) = F(m_0) \left[\frac{\eta \, m}{\eta \, m_0} \right]^{1-s} = F(m_0) \left[\frac{E_d(m)}{E_d(m_0)} \right]^{1-s} . \tag{5}$$

By taking the logarithm of the above expression we arrive at

$$\log F(E_d) = C + (1 - s) \log E_d, \tag{6}$$

where C embodies constants that are not relevant for the analysis. From this equation it is clear that the logarithm of the observed cumulative number of impacts vs the logarithm of the energy received on Earth can be fitted by a straight line whose slope yields the mass index s. Caution must be taken in the analysis because the probability of detection of flashes decreases with E_d. In particular, the true number of faint events will be larger than the observed one. At present it is difficult to estimate
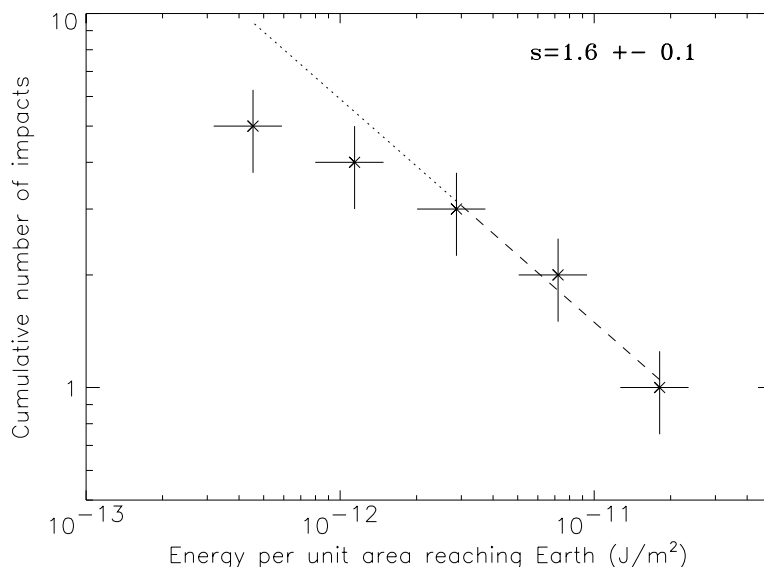
Figure 3. Logarithm of the observed cumulative number of impacts vs. the logarithm of E_d for the 1999 lunar Leonids. The straight line is the best fit to the points with $E_d > 2 \times 10^{-12}$ J m^{-2}. The statistics are poor, but the cumulative number of impacts is reasonably well described by a mass index $s = 1.6 \pm 0.1$.

such detection probabilities, but a rigorous treatment must include a proper correction, much as it is done in the analysis of visual meteor observations (e.g., Koschack and Rendtel, 1990).

Figure 3 shows the logarithm of the cumulative number of impacts as a function of $\log E_d$ for the 1999 lunar Leonids. In order to minimize the effect of our lack of knowledge of detection probabilities, the fit is performed only for the brightest events $(E_d > 2 \times 10^{-12}$ J m$^{-2})$, that is, those that cannot be missed because of their high signal-to-noise ratios. Despite the small number of events available, the distribution is well described by a mass index $s = 1.6 \pm 0.1$. This value is somewhat smaller than the index $s = 1.83$ derived from the 1999 Leonid fireballs in the magnitude range -1 to -6 (Arlt, *et al.*, 1999), but the agreement is remarkable in view of the limited data set on which our analysis is based.

3.3. IMPACTOR MASSES

Once luminous efficiencies are known, impactor masses can readily be obtained from Eq. 3 by inserting the measured value of E_d and noting that $E = mV^2/2$. The mass of the Leonid meteoroids that produced

the brightest lunar flash in 1999 turns out to be 4.9 kg if $\eta = 2 \times 10^{-3}$ is assumed (Bellot Rubio, Ortiz, and Sada, 2000). Arguments supporting the view that impactor masses are uncertain by less than a factor of 10 have been given by these authors. Such particles correspond roughly to terrestrial Leonids of magnitude -10 according to Hughes (1987).

An additional, alternative method can be envisaged for determining the total mass of the meteoroids striking the Moon. This technique consists in the monitoring of the lunar sodium during moments of high meteoroid activity to search for changes in the Moon's tenuous sodium atmosphere, which is believed to be partially maintained by impact-driven vaporization of surface material (see, for example, Morgan *et al.*, 1989, and references therein). The usefulness of this method is somewhat dependent on reliable models of the impact process as well as on a detailed treatment of the dynamical evolution of sodium in the lunar atmosphere. In spite of these difficulties, however, the method shows great promise, as transient enhancements of atmospheric sodium have already been detected at the time of the 1997 and 1998 Leonid showers (Hunten *et al.*, 1998; Verani *et al.*, 1998; Wilson *et al.*, 1999).

3.4. CRATER SIZES

Knowledge of impactor masses makes it possible to estimate crater sizes. Although no experiments on hypervelocity impacts involving meteoroids such as those striking the Moon have been conducted, the results of more conventional experiments can be scaled for a prediction of crater diameters resulting from lunar impacts. Gault's (1974) scaling law for craters up to 100 m in diameter in regolith reads

$$D = 0.25\, \rho_{\mathrm{p}}^{1/6}\, \rho_{\mathrm{t}}^{-1/2}\, g^{-0.165}\, W^{0.29} \sin^{1/3}\theta, \tag{7}$$

where D is the (transient) crater diameter, ρ_{p} and ρ_{t} are the projectile and target bulk densities, respectively, g is the gravitational acceleration, W is the impactor's kinetic energy, and θ the incidence angle with respect to the vertical (all in mks units). For the Moon, appropriate values are $g = 1.67$ m s^{-2} and $\rho_{\mathrm{t}} = 3000$ kg m^{-3}. Another estimate has been provided by Schmidt and Housen (1987):

$$D = \gamma^{-0.26}\, m^{0.26}\, V^{0.44}, \tag{8}$$

where m and V are the mass and speed of the impactor, respectively, and

$$\gamma = 0.31\, g^{0.84}\, \rho_{\mathrm{p}}^{-0.26}\, \rho_{\mathrm{t}}^{1.26}\, (\sin 45/\sin\theta)^{1.67}. \tag{9}$$

As pointed out by Melosh (1989), these formulae result in similar crater diameters in spite of their different origins. This is especially true for

small energy events, i.e., the case of meteoroids impacting the Moon. However, they must be applied with care because they were obtained for intermediate impact velocities of 10–20 km s^{-1}.

Assuming a bulk density $\rho_\mathrm{p} = 1000$ kg m^{-3}, the above expressions lead to crater diameters of 11 and 32 m, respectively, for the biggest 1999 Leonid impactor ($m = 4.9$ kg). With $\rho_\mathrm{p} = 100$ kg m^{-3}, one finds 7 and 27 m, respectively. Craters of this size are well below the resolution capabilities of telescopes on Earth, but may be detected on high resolution images by spacecraft orbiting the Moon. Three such missions are scheduled for 2002 and 2003: ESA Smart 1 (about 50 m/pixel resolution), ISAS Lunar A, and ISAS Selene. Only in exceptional cases should we expect larger craters, as the diameter is mainly determined by the velocity of the impactor and the Leonids possess the highest speed among the various meteoroid streams.

4. Numerical simulations

The detection of Leonid flashes on the Moon has triggered some very recent impact modeling efforts. Contrary to previous simulations, the new ones include the basic properties of meteoroid particles (comet-like composition, low density, high velocity, etc). The work of Artemieva, Shuvalov, and Trubeskaya (2000) deserves special mention. These authors simulated the vertical collision of Leonid particles on the Moon by means of a 2D hydrodynamical code. Vertical instead of oblique incidence was assumed on the basis of previous simulations where the luminous efficiency did not vary much with the entry angle.

According to the results of Artemieva *et al.* (2000), the flashes are mainly the result of thermal emission from hot plasma plumes created by vaporized meteoroid and target material. The whole process takes place on a very short time interval, of the order of 10^{-3} s. The first stage is characterized by the plasma being optically thick. The temperature drops rapidly and the gas becomes optically thin, leading to increased radiation fluxes. Artemieva *et al.* (2000) find some evidence that meteoroid bulk densities of 100 kg m^{-3} are to be preferred with respect to 1000 kg m^{-3} in order to explain the observed duration of the flashes. By integrating the radiative flux over time, they obtain theoretical luminous efficiencies of 10^{-3} for 1000 kg m^{-3} particles and 2×10^{-3} for 100 kg m^{-3} meteoroids. Moreover, the luminous efficiency is found to vary little (to within 10–20%) with impactor mass.

The uncertainties in this kind of simulation may be reduced to some degree by observational input. For example, the short duration of the flashes suggests that Leonids are very low density meteoroids. Larger

densities would lead to longer durations that are not consistent with the observations. Another example comes from the remarkable similarity between the luminous efficiencies resulting from the Artemieva *et al.* simulations and the analysis of the 1999 lunar flashes by Bellot Rubio *et al.* (2000). This agreement suggests that the experimental value of η is essentially correct (at least for the Leonid lunar impacts), which in turn validates the results of the numerical calculations.

Impact flashes contain much more information than can be extracted at the present time. The shape of the light curve is determined by, among other factors, the chemical composition of the lunar soil and the meteoroid. Obtaining such light curves with sufficient temporal resolution would allow us to infer these compositions, but this is a difficult observational endeavor due to the extremely short duration of the flashes. Spectroscopic analyses of the radiation generated during impacts are also of great interest for determining chemical compositions. Advances in these directions can be expected in the future as new instrumentation becomes available.

5. Detectability of impacts on the Moon

The probability of detecting optical flashes on the Moon at the time of a meteoroid shower is determined by several factors, among them geometrical conditions (position of the subradiant point on the Moon and lunar phase), the specifics of the observational technique (telescope optics and background illumination from the day side of the Moon), and properties of the meteoroids themselves (such as particle speed and spatial density). In this section we describe these contributing factors in some depth.

5.1. Geometric considerations

Not all meteoroids striking the Moon can be observed from Earth. First, it is necessary that the subradiant point position on the Moon allow impacts to occur on the lunar hemisphere facing the Earth. This condition is always fulfilled unless the radiant lies at selenographic longitude 180° and latitude 0°. However, the lunar area perpendicular to the meteoroid direction (the quantity determining the efficiency of the Moon as a particle collector) will decrease with increasing angular distance of the subradiant point to the Earth-facing hemisphere. Second, it is necessary that impacts take place on the night side of the Moon as seen from Earth. This constraint stems from the need of a high signal-to-noise ratio for unambiguous detection of the light flashes.
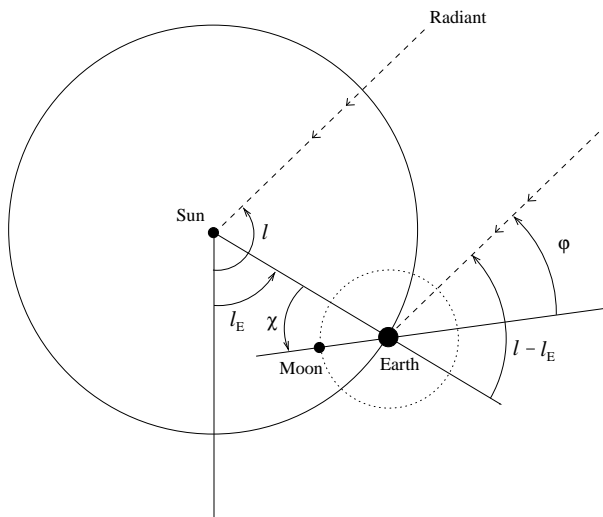
5.1.1. *Subradiant point on the Moon*

For a given shower, the selenographic coordinates of the subradiant point (φ, λ) are calculated from the equatorial coordinates of the radiant (α, δ) as determined from Earth, the location of the Earth in its orbit with respect to the Sun (via the solar longitude $l_\odot$), and the location of the Moon with respect to our planet at the time of the shower's maximum activity. In order to simplify the calculations, we make the approximations that the inclination of the lunar orbit to the ecliptic is zero and that the rotation axis of the Moon points exactly toward the ecliptic north pole. These approximations are reasonable because the inclination of the mean lunar equator to the ecliptic is of the order of 1.5° and will allow us to compute the position of the Moon by using the lunar phase only. The first step is to transform the equatorial coordinates of the radiant to ecliptic coordinates (l, b) by means of standard formulae. Both l and b define the direction of the meteoroid trajectories in the vicinity of the Earth. The ecliptic coordinates of the Earth are given by $l_E = l_\odot + 180°$ and $b_E = 0°$. Finally, the position of the Moon with respect to the Earth is given by the lunar phase angle χ, defined to be zero at new Moon, 90° at first quarter, and so on. Our simplifying assumptions imply that the ecliptic latitude of the Moon is zero.

Figure 4 displays the encounter geometry. It is clear that the selenographic longitude of the subradiant point is $\varphi = l - l_E - \chi$, whereas the selenographic latitude must coincide with the ecliptic latitude of the radiant (i.e., $\lambda = b$) because of our approximation that the lunar equator has a zero inclination to the ecliptic. At this point we note that selenographic longitudes are measured from the central meridian counterclockwise as seen from the lunar north pole.

5.1.2. *Lunar area subject to impacts*

The total area of the night side of the Moon perpendicular to the meteoroid direction and visible from Earth, $A_\perp$, is a measure of the efficiency in detecting impacts. Other parameters have been proposed to indicate how favorable the encounter geometry is (e.g., Beech and Nikolova, 1998), but $A_\perp$ is more intuitive and useful for further calculations.

$A_\perp$ depends on the selenographic latitude λ and longitude φ of the subradiant point, as well as on the lunar phase. As before, we make the simplifying assumption that the inclination of the Moon's orbit to the ecliptic is zero. Given the complex geometry, a fast and efficient way to compute $A_\perp$ is Monte Carlo simulations. Let xyz be a reference frame with origin at the center of the Moon, the x-axis pointing towards the Earth, and the z-axis pointing towards the ecliptic north pole. This system defines the selenographic coordinates of any point on the

Figure 4. Geometry for the calculation of the selenographic coordinates of the sub-radiant point on the Moon. The Earth–Moon distance has been exaggerated for clarity (indeed, the ecliptic longitudes of the Moon and the Earth are the same for practical purposes). The selenographic coordinates refer to a cartesian coordinate system centered on the Moon with the x-axis pointing to the Earth and the z-axis to the ecliptic north pole. The meteoroid's direction is indicated by the dashed lines.

Moon's surface. Meteoroids strike the Moon homogeneously distributed in planes perpendicular to the radiant direction. Hence, we define the auxiliar coordinate system XYZ by rotating the xyz system until the z-axis points toward the radiant. This is equivalent to a rotation of angle φ around the z-axis and a rotation of angle $\theta = \pi/2 - \lambda$ around the y-axis. In this coordinate system, we generate a sufficiently large number of particles uniformly distributed in the XY plane and such that their coordinates verify the condition $X^2 + Y^2 \leq 1$. Next, the corresponding (positive) Z coordinates are obtained by means of the equation of a sphere. The set of XYZ coordinates represents the locations of particles impacting the Moon. In order to compute $A_\perp$, it is necessary to know how many such particles are visible from Earth. To that aim, the XYZ coordinates are transformed back to the xyz system,

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos\theta\cos\varphi & -\sin\varphi & \sin\theta\cos\varphi \\ \cos\theta\sin\varphi & \cos\varphi & \sin\theta\sin\varphi \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (10)$$

and their selenographic longitudes calculated. Only those particles lying on the night side of the Moon (i.e., whose longitudes are between that of

the terminator and the non-illuminated limb) are counted. The number of such particles over the total number of particles, multiplied by πR^2 (with R the Moon's radius), gives the lunar area of the night side of the Moon perpendicular to the radiant direction. Note that optimum geometric conditions ($\lambda = 0$, $\varphi = 0$, and new Moon) imply $A_\perp = \pi R^2$. This is the maximum cross-section of the Moon as a particle detector. Obviously, the larger the value of $A_\perp$, the better the observability of the shower from Earth. Throughout we have assumed the meteoroid velocity is big enough (> 40 km s^{-1}) so that no gravitational deflection and focusing by the Moon or the Earth occurs. This is actually the case for all meteoroid streams whose observation is of interest.

The method used to compute $A_\perp$ can be extended to derive the lunar area perpendicular to the meteoroid direction within the field of view, A, which is necessary for the calculation of the expected cumulative number of impacts (Eq. 2) for a given telescope setup. Both the position and size of the camera field of view need to be considered for calculating A, but this is the only modification required to apply the above procedure.

Increasing the detection rate may be achieved by centering the field of view as close as possible to the subradiant point on the Moon while keeping the terminator at the greatest distance possible, since this will increase A. If the subradiant point lies on the hidden lunar hemisphere (a situation often met), then the angular distance of the center of the field of view to the subradiant point should be minimized. In that case, observations near the limb are recommended.

5.2. Signal-to-noise considerations

The signal-to-noise ratio (SNR) for the detection of an impact flash in a single detector element is, approximately,

$$\frac{S}{N} = \frac{0.5mV^2\eta\pi r^2Q}{2\pi R^2 h\nu \left[\frac{0.5mV^2\eta\pi r^2Q}{2\pi R^2 h\nu} + d_c(t) + M_b(t) + R_n^2\right]^{1/2}} \quad (11)$$

with η the luminous efficiency, R the Earth–Moon distance, m the meteoroid mass, V the meteoroid speed, h Planck's constant, ν the frequency of the radiation, Q the quantum efficiency of the detector, M_b the Moon brightness (in electrons), R_n the read-out noise (in electrons), d_c the dark current (in electrons), r the telescope aperture radius, and t the integration time.

According to Melosh *et al.* (1993), a single element detector such as a photomultiplier would be able to record impacts of meter-sized meteoroids. They quoted a threshold sensitivity of 10^{-6} W m^{-2} for

a photomultiplier coupled to a 1 meter telescope. CCD arrays are far more sensitive because M_b is considerably smaller in each pixel (due to the small angular size of a single pixel compared to the photometer's aperture) and also because quantum efficiency is usually higher in CCDs. For a typical image scale of 1 arcsec/pixel, M_b is several orders of magnitude smaller using CCDs than using a photometer with a 10 arcmin aperture.

The background brightness is mainly due to scattered light from the Moon's day side, but it also has a contribution from the Earth-lit surface of the lunar night side, which is not completely dark. Scattered light from the day side depends on the atmospheric conditions at the observing site as well as on the optics of the telescope. For typical observing conditions, with a lunar illumination of 20–30 per cent, the brightness of the night side of the Moon is of order $m_v = 12$ mag arcsec^{-2}, but reaches brighter magnitudes as the lunar phase increases. For the 1999 Leonid campaign, it was close to 8 mag arcsec^{-2}.

The easiest way to increase the SNR is to decrease M_b. This can be achieved by using short integration times. Since the light flashes are very brief (of the order of 0.02 s), reducing the exposure time results in better SNRs because the signal is not modified. Obviously, the larger the distance between the subterrestrial and subsolar points, the smaller the background brightness. This means that the best viewing conditions occur at new Moon, but the angular separation between the Moon and the Sun is too small to allow observations. The optimum viewing conditions are therefore those with the Moon being a few days before or after new Moon, with phase angles between 70° and 90° or between 270° and 290°.

In addition, the SNR might be higher in the near infrared than in the visible because more energy should be radiated as a result of the larger plume size when the plasma is cold enough to emit in the near IR; that is, the luminous efficiency should be higher. Another advantage of the infrared is that the scattered radiation from the day side of the Moon is lower than in the visible. The main drawback of infrared observations is the fast variation of the sky brightness, which often shows significant differences on time scales of the order of minutes.

5.3. OTHER CONSIDERATIONS

A number of additional factors influence the visibility of lunar impact flashes. First, it is clear that the likelihood of detecting impacts depends on the amount of energy released in the process. Impacts caused by meteoroids moving at high speeds will be much easier to detect simply because the energy reaching Earth goes as the velocity squared. Second,

Table II.

| Shower | Max | $l_\odot$ (deg) | Radiant coordinates | | | | V | s | $F_{6.5}$ |
			α	δ	l	b			
QUA	Jan 4	283.16	230	49	201	63	41	1.91	0.03
ETA	May 5	45.5	338	−01	339	8	66	1.99	0.04
PER	Aug 12	139.8	46	58	62	39	59	1.95	0.07
ORI	Oct 21	208.0	95	16	95	−07	66	2.06	0.01
LEO	Nov 17	235.27	153	22	147	10	71	1.92	0.03
GEM	Dec 13	262.0	112	33	109	11	35	1.95	0.06

it is necessary that the spatial density of meteoroids is sufficiently large to ensure that particles will strike the Moon during the observations. Not all meteor showers produce high fluxes of meteoroids, so monitoring of the Moon is preferable when the major annual showers peak on Earth.

Another consideration is integration time. Although the events are bright (the magnitude of the brightest flash during the 1999 Leonids was +3), the use of magnitudes can be misleading. Indeed, the optical flashes are very intense, but only *during extremely short time intervals*. It is therefore convenient to reduce the integration time as much as possible in order for the background not to hide the signal coming from the impact. In this regard, CCD video cameras or very fast readout CCDs are necessary for increasing the detection probability.

6. Estimating impact detection rates

In this section we use the previous results for examining the observability of a number of annual showers on the Moon during the next five years. The Quadrantids, η Aquarids, Perseids, Orionids, Leonids, and Geminids have been selected because of their high velocity and/or high flux of meteoroids. As mentioned before, high velocities imply that more energy is radiated, making the light flashes easier to detect from Earth. High fluxes mean more particles colliding with the Moon and higher likelihood of observing impacts. Special attention is paid to the forthcoming Leonid showers in view of the greatly enhanced fluxes expected in 2001 and 2002.

Table II summarizes basic observational parameters for the Quadrantids (QUA), eta Aquarids (ETA), Perseids (PER), Orionids (ORI), Leonids (LEO), and Geminids (GEM) according to the IMO meteor

shower working list (Rendtel *et al.*, 1995). The second column gives the date of maximum activity. Solar longitudes ($l_\odot$, J2000.0) and radiant coordinates refer to this date. V is the meteoroid's velocity, s the mass index in the visual range, and $F_{6.5}$ the maximum flux of meteoroids brighter than magnitude +6.5 in $\mathrm{km}^{-2}\,\mathrm{h}^{-1}$.

From the values of s and $F_{6.5}$, it is possible to estimate the number of events detectable from Earth during one our of observing with different instruments. Table III shows the results for 0.2 m f/10 and 1 m f/2 telescopes (columns N_1 and N_2, respectively) assuming that the lunar area perpendicular to the meteoroid's direction within the field of view is $A \sim 10^6\,\mathrm{km}^2$. These figures have been computed according to Equation 2 with $\eta = 2 \times 10^{-3}$ and threshold energies taken from Fig. 5. It is very important to stress here that the number of events is strongly dependent on the value adopted for s. The mass indices quoted in Table II refer to the average value of s during the period of shower activity, but very often s decreases at the time of maximum activity. Smaller mass indices mean that large particles are more abundant, leading to increased detection rates. For this reason, values in Table III must be taken as rough lower limits. According to our estimates, one may expect of the order of 4–11 and 1–2 impact flashes per hour in the field of view during the Quadrantid, Perseid, and Geminid maxima with 1 m f/2 and 0.2 m f/10 telescopes, respectively.

In order to quantify the visibility of the showers in terms of $A_\perp$, the time of maximum activity is calculated from the solar longitude $l_\odot$ for each year from 2001 to 2005. The phase of the Moon at that time is also computed to derive the selenographic coordinates of the subradiant point. The results are presented in Table IV. The fifth and sixth columns give the selenographic latitude and longitude of the subradiant point at the time of maximum activity. χ is the lunar phase (0° for new Moon, 90° for first quarter Moon, 180° for full Moon, and 270° for last quarter Moon). $A_\perp$ (normalized to πR^2) varies from 0 (impacts not visible) to 1 (best geometrical conditions). For comparison, $A_\perp$ was $0.44\,\pi R^2$ at the time of the 1999 Leonid shower maximum (with $l = 147.7°$, $b = 10.2°$, $l_\odot = 235.367°$, and $\chi = 111.8°$). The data for the 2001 and 2002 Leonids refer to the peak times on Earth predicted by McNaught and Asher (1999) plus the time needed by the Moon to reach the same ecliptic longitudes (2.5 h in 2001 and 0.5 h in 2002).

Favorable conditions will occur for the showers whose $A_\perp$ values are in bold type. Normally, showers with very high $A_\perp$ values occur near new Moon. They are of no interest because the Moon cannot be observed for a long time under dark skies. The best geometrical conditions occur for the Quadrantids in 2001, for the Perseids in 2002 and 2005, for the Orionids in 2001 and 2004, for the Leonids in 2001

Table III.

Shower	N_1	N_2	Shower	N_1	N_2
QUA	7.7	1.8	ORI	0.06	0.01
ETA	0.9	0.2	LEO	2.4	0.6
PER	4.1	0.9	GEM	10.7	2.3

and 2004, and for the Geminids in 2002. The visibility of η Aquarid impact flashes on the Moon is not good in any year except perhaps 2001.

6.1. EXPECTED DETECTION RATES FOR THE 2001 LEONIDS

According to McNaught and Asher (1999), the Earth–Moon system will cross in 2001 the dust trails generated by comet Tempel–Tuttle nine and four revolutions ago. Maximum activities are somewhat uncertain at the moment, but ZHR values of about 15000 for each trail have been suggested. The closest approach of the Earth to the two trails is predicted for November 18, 2001 at 17:31 and 18:19 UT, respectively. The Moon will reach the same ecliptic longitudes about 2.5 hours later. As can be seen in Table IV, the lunar phase will be 42°, while geometric conditions are rather favorable with $A_\perp = 0.50\,\pi R^2$. This makes the 2001 Leonid shower an excellent candidate for producing lunar impact flashes. Europe is badly placed because the maximum will occur at moonset or later, whereas Brazil is probably the best location for recording the peak with the Moon at a sufficient altitude above the horizon. Even if the Moon cannot be observed from a given location at the time of maximum activity, observations before or after the peak will be very valuable, as some impacts might still be detected (see Table III for detection rates of Leonid flashes under non-storm conditions). In any case, the Moon will be in a dark sky for a short time period, so infrared observations may be advantageous.

Figure 5 shows the cumulative number of impacts detectable from Earth per hour of observation of a lunar area of 10^6 km^2, as a function of the energy reaching Earth. The lunar area of 10^6 km^2 is in the direction perpendicular to the radiant; this area is close to that observed using a conventional CCD video camera attached to a 0.2 m, f/10 telescope aimed at the subradiant point on the Moon. The three curves are predictions for several luminous efficiencies (5×10^{-3}, 2×10^{-3}, and 10^{-3}). The vertical lines represent the sensitivity thresholds of different telescopes. Asterisks mark the predicted cumulative number

Table IV.

Shower	Year	Date	Hour (UT)	Subradiant λ	φ	χ (deg)	$A_\perp$ ($\times \pi R^2$)
QUA	2001	Jan 3	12	63	1	97.3	**0.33**
	2002	Jan 3	18	63	−144	241.9	0.08
	2003	Jan 4	00	63	85	13.4	0.45
	2004	Jan 4	06	63	−49	146.8	0.16
	2005	Jan 3	12	63	−169	266.8	0.12
ETA	2001	May 5	23	08	−48	272.3	0.13
	2002	May 6	06	08	−178	53.7	0.00
	2003	May 6	12	08	57	188.7	0.30
	2004	May 5	18	08	−7	317.9	0.00
	2005	May 6	00	08	144	83.1	0.10
PER	2001	Aug 12	12	39	−170	272.3	0.04
	2002	Aug 12	18	39	48	53.7	**0.40**
	2003	Aug 12	23	39	−87	188.7	0.00
	2004	Aug 12	06	39	144	317.9	0.17
	2005	Aug 12	12	39	19	83.1	**0.38**
ORI	2001	Oct 21	09	−7	11	56.2	**0.69**
	2002	Oct 21	15	−7	−114	180.8	0.00
	2003	Oct 21	21	−7	114	313.0	0.30
	2004	Oct 21	03	−7	−26	92.6	**0.64**
	2005	Oct 21	09	−7	−160	226.1	0.00
LEO	2001	Nov 18	20	10	49	41.6	**0.50**
	2002	Nov 19	11	10	−83	173.1	0.06
	2003	Nov 18	02	10	170	282.3	0.01
	2004	Nov 17	08	10	28	64.4	**0.48**
	2005	Nov 17	14	10	−105	197.9	0.00
GEM	2001	Dec 13	23	11	38	348.4	0.89
	2002	Dec 14	06	11	−92	118.7	**0.42**
	2003	Dec 14	12	11	142	244.4	0.11
	2004	Dec 13	18	11	4	22.9	0.94
	2005	Dec 14	00	11	−133	159.3	0.11

of detections using the different instruments. Note that 1 m f/10 telescopes would record a smaller number of flashes because the total area comprised in the field of view is considerably smaller than with the other instruments. For these calculations a background brightness of 12 mag arcsec^{-2} and a cumulative flux of 10 meteoroids km^{-2} h^{-1}
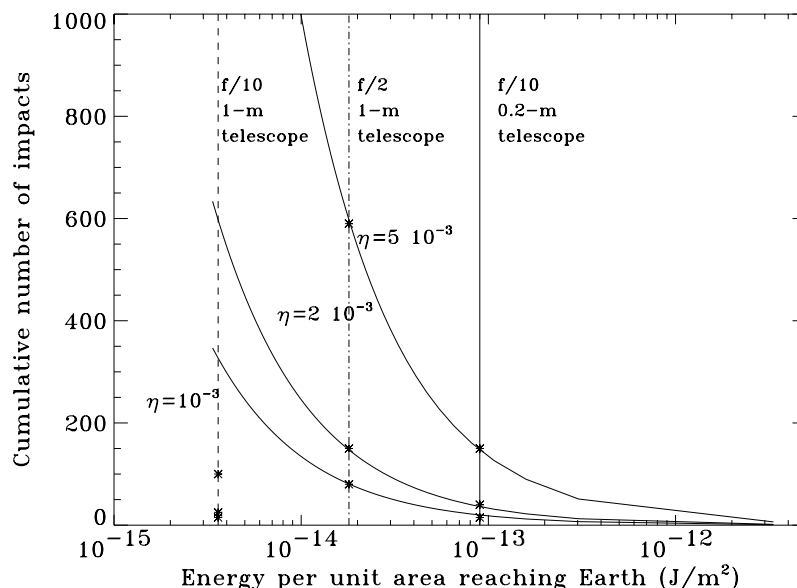
Figure 5. Expected number of detections of 2001 Leonids during one hour of observing for several telescopes and luminous efficiencies (solid lines). The sensitivity thresholds of the different telescopes are indicated by the vertical lines. They have been obtained assuming typical values of quantum efficiency, readout noise, etc. The actual number of detections depends on the field of view of the telescope, and is represented by asterisks. A Leonid flux of 10 km^{-2} h^{-1}, equivalent to ZHRs of about 30000 on Earth, and $s = 2.0$ have been used for the calculations.

with masses higher than 0.02 mg have been assumed. This flux would be equivalent to a zenithal hourly rate of roughly 30,000 on Earth. The calculations can be scaled to different areas and different fluxes by simply multiplying the curves by the appropriate factor. With small 0.2 m telescopes, up to 40 impact flashes can be expected within the field of view during one hour of observing. The number of flashes increases for 1 m telescopes at f/2. These may record up to 150 flashes in one hour if the flux of Leonid meteoroids reaches the predicted value.

7. Concluding remarks

The 1999 lunar Leonids have demonstrated that CCD cameras attached to telescopes of even 0.2 m in diameter can successfully detect light flashes of meteoroids impacting the Moon. Careful analyses of the observations provide a great deal of information on the physics of hyper-velocity impacts and the properties of meteoroids and meteor streams.

The new technique, however, still awaits full exploitation. Observations with different telescope setups and in different wavelength ranges will certainly increase the number of events available for analysis. Only when a sufficiently large database has been accumulated will the investigation of topics such as the dependence of the luminous efficiency on velocity and mass be possible.

Almost all meteor showers visible from Earth can be observed on the Moon. However, it is necessary that the flux of particles and the meteoroid velocity be large enough to ensure high detection rates. As a consequence, only the major annual showers deserve close scrutiny. We have described in detail the various conditions for the visibility of impact flashes on the Moon with a view to provide predictions for the next few years. The most promising showers are the Quadrantids in 2001, the Perseids in 2002 and 2005, and the Geminids in 2002. No doubt, the 2001 Leonid return will be the best candidate if the meteoroid flux turns out to be as high as expected. Concerning the 2002 Leonid shower, a nearly full Moon along with very bad geometric conditions will render any observational effort almost worthless.

Acknowledgements

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